

Full Scale Injection of Coal Combustion Byproducts into an Underground Mine to Control Acid Mine Drainage and Subsidence.

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Abstract

This paper presents the results of a study involving the field scale injection of grouts into underground room and pillar mines to control acid mine drainage and subsidence. Two grouts are discussed in the paper. The first is a Fluidized Bed Combustion (FBC) ash grout. The second is a grout made of high loss on ignition (LOI) ash and cement kiln dust (CKD). Both mixes were developed from several laboratory scale experiments conducted to investigate flow characteristics and strength of the grouts. Based on the rheological properties of the FBC ash grout it was determined that admixtures were needed to stabilize it for optimum flow characteristics. Strength requirements for the grouts were determined from site specific geologic information and expected stress levels. One thousand cubic yards of the FBC ash grout were pumped into an inactive panel of an active room and pillar coal mine to investigate the field performance of the grout. The field study showed that a grout made of FBC ash can be successfully pumped to backfill the mine void. Given that most of the FBC ash produced in the region is used for alkaline amendments at surface mines an alternative grout mix was chosen for the Longridge demonstration. In the Spring of 1998, 53,000 yd³ of the high LOI/CKD grout will be pumped into the Longridge Mine in Preston County, West Virginia.

Introduction

The original goal of the project (U.S. DOE/WVU Cooperative Agreement DE-FC21-94MC29244) was to fill an underground mine with FBC ash grout using as few injection holes as possible, due to the cost involved in drilling the holes. As a consequence, the distance the grout may be made to flow or the 'flowability' of the grout is of utmost importance to the project feasibility. The settling that occurs in unstable grouts may reduce the maximum flow distance to such a degree as to render the project impractical. One purpose of this project was to study the subsidence potential at abandoned mines, which have been backfilled with a grout. The study also includes a discussion on the strength requirements of grout and grout backfill configurations to be used for mitigation of subsidence potential at an abandoned mine.

Grout Instability

Initially on the project, observations on mixes of the FBC ash and water showed some settling. When experiments for the pressure drop across a tube were being set up, the ash and water mix locked up and there was no flow. This was an indication that settling was occurring. An attempt to perform rheological testing with a parallel rotating plate rheometer failed as the mix was settling.

Other tests done on the rotational viscometer using the T-bar spindle gave proof that particles in the pure FBC ash - water grouts were settling. First a series of tests was done in which the spindle was rotated at a constant speed while being moved up and down through a grout containing only the fly ash fraction of FBC ash. Torque readings were taken at five second intervals for the length of the test. When these readings were plotted versus time, the pattern showed that the torque increased as the spindle neared the bottom of its path, and decreased as it neared the top of the path, as seen in Figure 1. This periodic behavior is due to the variation in the length of the submerged shaft, but the increase in amplitude is due to the settling of the particles causing the lower portion of the sample to become more concentrated than the upper portion.

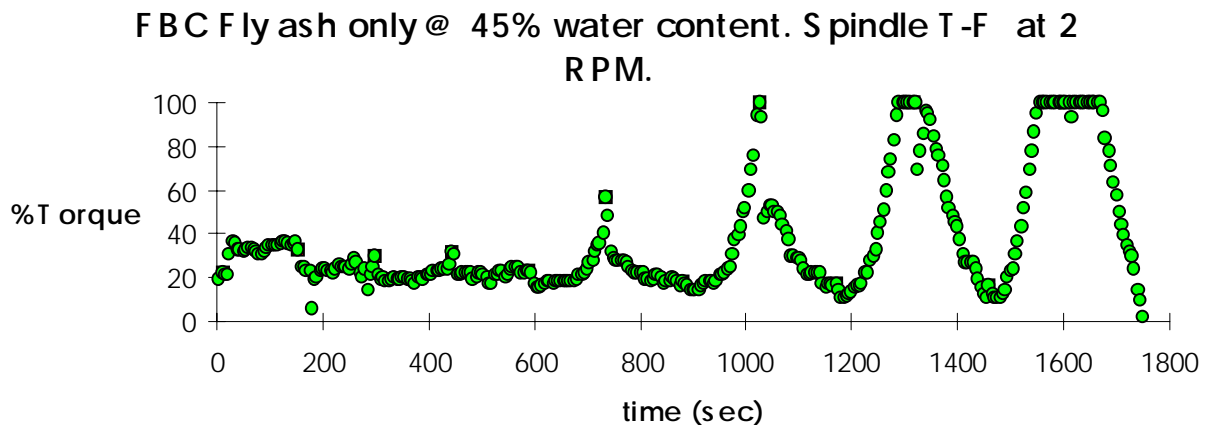


Figure 1 Plot showing how settling affects torque.

The concentration of solid particles varies with time and space because of gravity settling, implying that the grout becomes inhomogeneous. As the concentration of particles increases at the bottom of the grout mixture, friction will develop between the solid particles. This Coulomb friction acts as an additional resistance to the flow of the grout and must be included in the rheological constitutive law used to define the grout mixture. For parallel shear flow of a Herschel-Bulkley fluid this relation is given as:

$$\tau = \tau_y + k(\dot{\gamma})^n + P\mu_f$$

where τ = shear rate

τ_y = yield stress

k = consistency index

$\dot{\gamma}$ = strain rate

n = flow index

P = pressure

μ_f = friction coefficient

When there is no flow (i.e., $\dot{\gamma}=0$) the residual shear stress may be as large as:

$$\tau = \tau_y + P\mu_f$$

Any yield stress fluid, stable or unstable, that is injected into a pipe or closed channel with a finite injection pressure, will eventually stop moving. Inevitably there will be a location downstream where the stress in the grout will fall below the yield stress at all points across the cross section, a solid plug will completely fill the pipe or channel, and flow will cease. For an unstable grout, Coulomb friction will further limit the extent of flow in a dramatic fashion. The hardening of the grout has been neglected in this discussion because the time required for hardening is much greater than the time scale of the flow.

Lombardi [1] used a balance of forces on grout that has come to rest to predict the maximum distance of spread for stable and unstable grouts. His formulae have been corrected [2], and used to demonstrate that it is impractical to use an unstable grout. The maximum flow distance for an unstable grout can be calculated to be about 4-5 times less than that with a stable grout, for a 500 psi pumping pressure and a 4-inch injection hole.

Grout Stabilization

By definition, an unstable grout is one that bleeds greater than five percent of its water during a two hour period. Bleed tests were done in accordance with ASTM standard C 232 - 87. Samples were prepared and placed in round containers that were covered to prevent evaporation. After two hours, any clear water that had bled to the surface was pipetted off and weighed. Mixtures of pure FBC ash and water were unstable. To combat the settling of the solid particles, various percentages of WYO-BEN 250 mesh bentonite was added to the grout mix. Figure 2 shows that the percentage of bleed increases linearly with an increase in water fractions, while the amount of bleed is decreased

by increasing the bentonite added. It was found that 5% bentonite was sufficient to render the grout stable for the water fractions of interest.

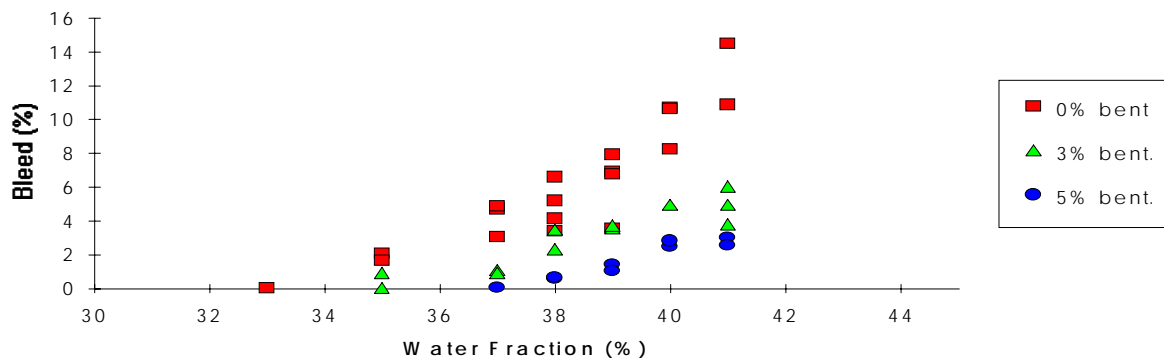


Figure 2 Results of bleed tests on mixes containing equal portions of fly ash and bottom ash.

Tests were then done using different water fractions and different amounts of bentonite. At 7 % bentonite, there was very little settling. Another test where the spindle was rotated at a constant depth was performed with torque readings taken at a specified time interval. Figure 3 shows that with no bentonite used in a fly ash only grout, the torque increased with time, but with 7 % bentonite, the torque at the constant depth showed much less increase. The increase in torque for the no bentonite grout is due to the settling of the ash particles. As the particles contact one another there is an additional frictional mechanism that increases the torque. Eventually, the T-bar formed a slip surface in the sample that effectively caused the torque to become constant. The sample containing bentonite, on the other hand, has less torque increase, showing that particle settling is not a problem. All these tests have shown that bentonite is an effective additive in the reduction of particle settling and in increasing the stability of the grout.

Ash Variability

Different samples of ash taken from the Morgantown Energy Associates Beechurst Avenue power plant not only contain varying percentages of fly and bottom ash, but also vary considerably in flow characteristics. This difference in behavior is likely due to the variability of fuel that the plant is burning and to the plant's method of collecting the ash. The power plant burns a mixture of pure coal, limestone, and "gob," which is refuse coal produced from the cleaning or washing of coal. Limestone is added to decrease the sulfur emissions from the exhaust stack. The percentage of gob burned is changed according to the output power requirements. Another cause of variability is due to the ash handling at the power plant. Every truck is filled from one of three ash holding hoppers. At any time these hoppers can contain any combination of fly and bottom ash.

The variability of the ash will require that the grout recipe be varied to maintain consistent flowability. The spread test was developed as a simple infield test to determine grout flowability. The spread test uses a cylinder 3 inches in diameter by 6 inches in height open at both ends. The cylinder is placed vertically on a horizontal surface and filled with grout. The cylinder is then slowly lifted and the grout is allowed to spread in a radial fashion. The distance of spread is then measured

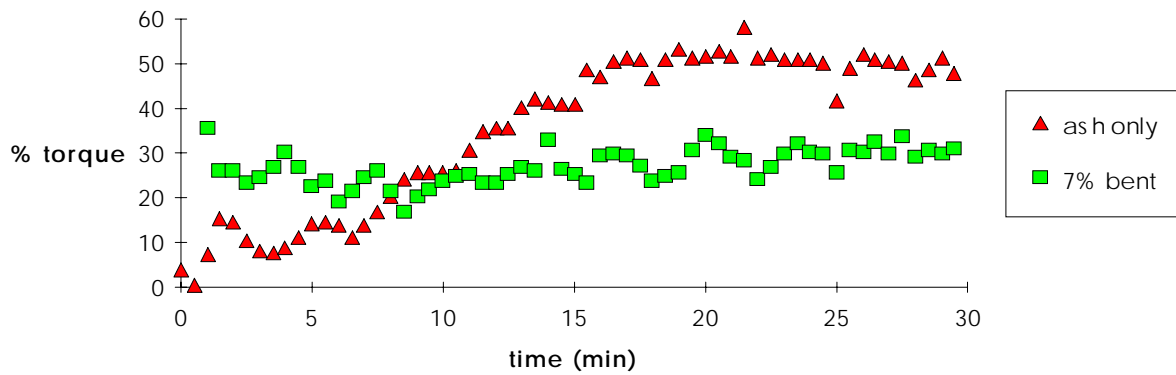


Figure 3: Plot showing increase in stability due to the addition of bentonite.

in two perpendicular directions and an average is taken. Spread tests were done using varying amounts of bentonite and water. Figure 4 shows how the addition of bentonite reduces the spread of the grout. The addition of a super-plasticizer and air entraining agents were considered to counteract the effect of the bentonite, but they proved to be too costly.

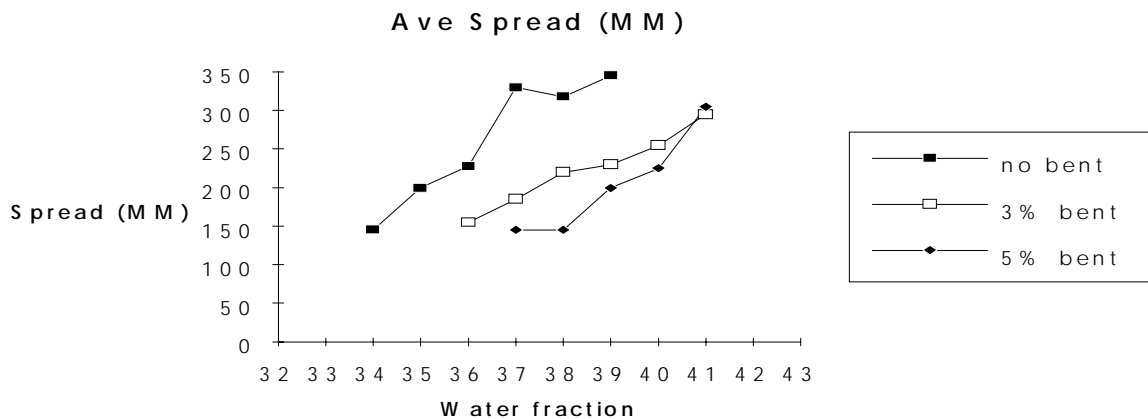


Figure 4 Spread versus water fraction for fly ash only samples at varying amounts of bentonite.

During the test injection at the Fairfax mine, this problem of ash variability was handled by choosing that amount of bentonite that gave the spread considered adequately flowable. Owing to the variability in the ash, a 5% bentonite recipe at the site gave the same spread as the 7% mix in the laboratory. Hence for the test injection a 5% bentonite recipe was adopted.

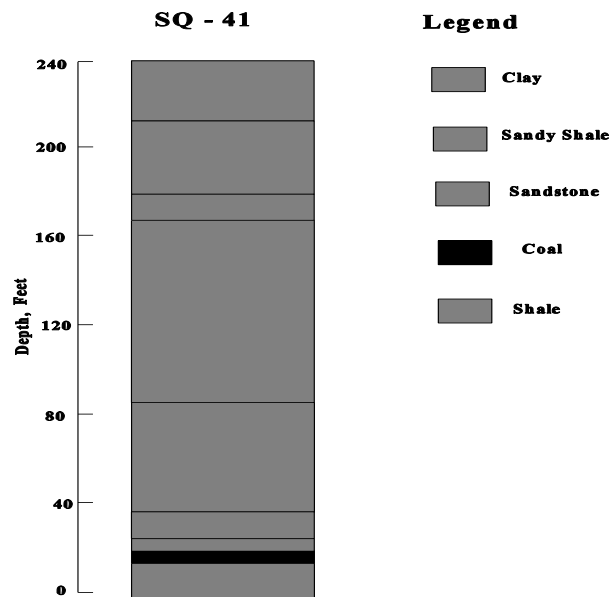
Grout Strength Requirements

Subsidence prediction, proper usages of damage mitigation techniques, and methods for mine backfill are essential prerequisites to control or reduce potential subsidence in abandoned room-and-pillar mines. Inadequate pillar support due to deterioration of pillars causes the overlying strata to

cave into the mine voids. This process propagates upward and finally reaches the surface. In room-and-pillar mining, it takes several years for surface subsidence to occur. Pumped slurry backfilling has been used in the past for controlling subsidence [5]. Subsidence is a function of the type of overlying strata, the depth of excavation and the method of mining.

Site Description

During field operations in May of 1996, the Fairfax mine was active mine in Preston County, West Virginia. The Upper Freeport coal seam is found at an approximate depth of 225 feet below the ground surface. The thickness of the coal seam is about 5 feet. Figure 5 shows the soil and rock stratigraphy at core hole location SQ41 at the Fairfax Mine. Information pertinent to these core holes was extracted from the bore hole logs obtained from the mining company. The geologic columns at the mine show that the thickness of a soft clay layer overlying the rock layers ranges from 19 to 28 feet. The rocks at the bedrock surface appear to be weathered. As shown in Figure 5, there is about 80 feet of weathered shale, which can be fairly massive and uninterrupted. Immediately below the top soil is a layer of sandy shale of about 15 to 20 feet in thickness. The Fairfax mine site is located in hilly terrain.



Note : This geologic column was made based on the information available on borehole logs

Figure 5 Geologic column at core hole location SQ-41 of Fairfax Mine.

Methodology for Analysis

Subsidence predictions and an estimate of the strength requirements of the grout to be used for backfilling the mine voids at the Fairfax and the Longridge mines are two of the major objectives of this study. Finite element analysis was performed to study the influence of varying backfill configurations on subsidence [7,8]. The effect of bulking of the fallen overburden rock into the mine cavity in reducing the subsidence potential was also considered in the analysis by using a bulking factor.

Strength calculations were based on the fact that the grout after being injected into the mine void should develop sufficient compressive strength to withstand the stresses caused by the overburden, along with the pillars. In effect, it should play the role of the excavated coal with its full strength. Traditionally, the vertical stress at the level of coal seam is calculated by multiplying the unit weight of the materials comprising the overburden with the respective thicknesses. However, the theoretical strength obtained by following the steps outlined above is not a true representation of the in situ strength requirement as some factors that affect grout strength, such as stress concentrations [4], have to be accounted for in the model. Moreover, pillar failures can affect the in situ stresses in pillars [6] and possibly surrounding areas. The state of stress around discontinuities such as mine cavities is three dimensional in nature, and hence it is difficult to obtain analytical solutions. A separate Finite Element Analysis [3] was performed to obtain information on stress concentrations around mine cavities.

Computed Grout Strength Requirements

Reasonably accurate prediction of subsidence potential is possible with growing usage of numerical methods like the Finite Element Method. Strength requirements of grout may vary with the method used for backfilling mine voids. In situ strength requirements of grout backfill materials are affected by various uncertainties such as;

- 1) Local geology
 - 2) Stress concentrations around mine cavities
 - 3) Segregation during placement of the grout
 - 4) Presence of water in mine cavities and the result of reactions between water and the various minerals present in the mine cavities on grout strength to name a few.
- Strength requirements found in the analysis may have to be multiplied by a factor of safety to account for these uncertainties. Also, the differences in laboratory and field conditions and strengths need to be considered.

Effect of Stress Concentrations Around Mine Cavities

In situ strength requirement varies from place to place and is a function of various factors such as segregation and stress orientations and stress concentrations. The variation of stress concentration factors was determined by varying elastic moduli and Poisson's ratio of the grout for two different overburden materials. This variation shows that the overburden stiffness has a marked effect on the stress concentration factors. For areas overlain by a stiff overburden the stress concentration factor around mine cavities appears to be close to 3.1. The values of the stress concentration factors comes

down with increase in the elastic modulus of the grout and reaches a value close to 1.0 for values of elastic modulus equal to that of the overburden. In the case of a weak overburden the stress concentration factor remains almost constant with a value close to 1.0 for different values of the elastic modulus of the grout after reaching a peak value of 3.16 for the cavity without any grout. For a grout that has a typical elastic modulus equal to 0.5 million psi, the value of the stress concentration factor appears to fall in the range of 2.5 to 2.75.

For a real situation, the overburden is likely to have a stiffness value in between the two scenarios considered in the previous section. In this study a value of 2.5 was assumed as a factor of safety to be used on the theoretical strength requirement of the grout to account for potential stress concentrations at the Fairfax and Longridge mines. Table 1 shows the computed strength requirements of the grout to be used as backfill material at the Fairfax mine. It should be noted that there are many other uncertainties such as those listed earlier, which were not considered in this study (for example, the effect of segregation during placement on grout strength, water content of the grout mix, etc.). Therefore, it would be prudent to investigate the effect of these uncertainties on the strength requirement of the grout and then obtain a factor of safety that accounts for all the factors affecting the grout strength. A fair measure of the strength requirement can be obtained from field observations of the grout performance at the Fairfax mine, where grout injections have been completed.

Table 1: Strength Requirements for the Grout at the Fairfax Mine

| Core Holes | Computed Stress at the level of coal seam (psf) | Stress (psi) | Factor of Safety to account for Stress Concentrations | Strength Requirement for the Grout (psi) |
|------------|---|--------------|---|--|
| SQ-41 | 34,495 | 239.0 | 2.5 | 600 |
| SQ-42 | 35,035 | 243.0 | 2.5 | 608 |
| SQ-43 | 32,815 | 227.0 | 2.5 | 570 |

Field Injection

Grout injection at the Fairfax mine has been completed. The locations of the wells were established so that a comparison can be made between wells located at interceptions and mid-sections of hallways. Two of the injection wells are located at interceptions of hallways. Two additional wells are located at the center of hallway sections. Below are observations made during the field injection process.

Observations on First Day: Injection began at 9:35 am, 21 May 1996. Johnnie Nichols, mine superintendent and Paul Ziemkiewicz were in the mine, 75 ft. from the injection borehole when injection began. FBC ash slurry was injected in batch mode from two alternating cement trucks on the surface. Each pour comprised about 9-10 cu yds of slurry. Each pour lasted about 20 minutes and the interval between pours was 5-10 minutes.

Pour #1 flowed 75 feet from the borehole. At the downstream end of the ash lobe its depth was about 1 inch. At the borehole the depth was about 2 inches. The ash front continued to advance until injection stopped. The slurry was very fluid, finding and progressively filling low spots. It formed a leveled channel between 1 to 2 foot wide with the narrower widths associated with higher flow rates over constrictions and overfalls. In incompletely filled headings, slurry flowed down the center line of a channel which was semicircular in cross section, ~4 foot wide and 3 inches high at the center line. These channels eventually became occluded, at which side channels would break out and initiate a new lobe.

Pour # 2 advanced a further 75 feet. Upon the subsequent pours, the slurry front remobilized with a roughly 1 minute lag time, initiated by a roughly ½ inch wave which propagated in line with the axis of advance. The wave was parabolic with its apex at the downstream end. The second pour did not ride over the first pour, rather it displaced it from the upstream end pushing the entire mass forward. Shale rocks (4-6 inches long, 2 inches square) were observed carried along with the slurry. Slurry velocity was 12 inches/sec at overfalls and more typically 6 inches/sec on the level floor.

Pour #3 advanced only another foot or so, but it spread out to fill two headings from pillar to pillar (18 ft heading width). At the end of pour #3 the thickness at the downstream end was 2 inches. A zone of bleed water about ½ inches was observed at the downstream end of the slurry. Between pours, when the slurry advance stopped a thin (1-2 mm) layer of bleed water could be seen moving slowly along the top of the slurry. At the end of Pour #3 slurry depths were 2 inches at the downstream end, 6 inches in a low spot at the first spad (center of intersection) and 4 inches at the borehole. There appeared to be some particle size segregation with higher sand contents at the borehole and in the main channels with more fines at the downstream end and in the side channels and bays.

Slurry flowed down the 1-2% slope of the mine floor. It would dam behind roof falls and floor irregularities then flow over or around. Pouring continued until 5:30 pm on the first day. About 125 cubic yards of slurry were injected on the first day. The slurry was warm to the touch but not uncomfortable (like bath water). It generated a good deal of vapor. Also, since AMD treatment water was used to make up the slurry, and the AMD was treated with NH_3 , contact with the lime caused deprotonation of the ammonium ion and release of more than perceptible amounts of NH_3 .

Observations on Second Day: Results of the previous day's injection: About 5,400 sq. ft. of mine floor were covered by the end of the first day to an average depth of about 8 inches. While floor elevation varied in the order of 1-2 ft from roof fall, the slurry had the effect of leveling to an almost planar surface. From an almost watery consistency the first day the slurry had set up slightly to a Jell-O consistency. At the end of the day one the injection crew ran about 800 gallons of water down the line to clean out the pump. This flushed out the slurry channels leaving them free for the next day's slurry.

Injection began at 7:30 am and while deforming the day one slurry in the immediate vicinity of the injection borehole, the new slurry flowed on top of the old slurry. It did not remobilize the old slurry to any significant extent. Since the FBC ash had been allowed to sit out overnight in a

thunderstorm, it had developed a crust. This was broken up into 2-3 in diameter chunks which were transmitted with the slurry. These could be seen floating by in the slurry channel.

With well developed channels, flow proceeded in surges particularly at constrictions and overfalls. Velocity would decelerate over a period of minutes, stop for a second or so, then release in a surge. The flow would then spread out evenly behind a small (1 in) wave below the overfall. Injection proceeded to 24 May 1996 until 1,000 cu yds were placed in the mine. The next in-mine visit occurred one week after injection on 31 May 1996.

Observations One Week After Injection: On 31 May 1996 a party consisting of representative from Fairfax Fuels, U.S. Department of Energy, CONSOL, Inc., WV Public Radio, Maryland DER, and WVU inspected the mine. By this time the slurry had solidified to the extent that samples had to be chopped out with an entrenching tool. In spots of > 6 inches of slurry it was still moist 3 inches from the top. The slurry had developed cracks which penetrated about 4 inches. These tended to run normal to the direction of ash flow. The ash had flowed about 550 ft from the injection borehole and surrounded four pillars. Headings were filled pillar to pillar and some rooms were filled with 2 ft of slurry (the roof was 4 ft high). At the injection borehole the slurry had coned but was still about 10 inches from the roof.

Conclusions Based on Fairfax Field Demonstration: The final strength of the FBC ash grout injected in to the Fairfax mine is 1150 psi. This is twice the strength needed to prevent subsidence. A grout made from FBC ash will be unstable and not flow without the addition of admixtures. The FBC ash/bentonite grout flowed over 600 feet from the injection borehole (see Figure 6).

Alternative Grout mix

The US DOE/WVU Cooperative agreement continues with the Phase III large scale demonstration project at the Longridge mine. The Longridge mine is an 11 acre room and pillar mine adjacent to the Fairfax mine in Preston County. The Phase II grout mix (FBC ash/bentonite) was planned to be used in Phase III. However, FBC ash has proven to be in short supply. All of the ash from the Morgantown Energy Associates power plant is backhauled by Anker Energy, Inc. Anker uses the FBC ash as an alkaline amendment for its surface mines in northern West Virginia. Additionally, the Omega Mine Project which will use FBC ash and Class F ash from Allegheny Power's Fort Martin power station further cuts into the available ash supply. With no new FBC units planned for the region, an alternative grout mix was sought.

Since Anker Energy is a partner in the DOE project with WVU, sources of ash were sought that Anker was backhauling from other fuel supply contracts. Additionally, a source of ash that would not "dry up" quickly was also sought. An answer was found at the Albright Ash station. Anker is backhauling a high LOI ash from a fuel supply contract out of state. The high LOI ash contains residual carbon due to the lack of oxygen in the combustion chamber. The oxygen starved combustor is one method of reducing a utility's NO_x (nitrogen oxides) emissions. Given the new Clean Air Act amendments which dictate reductions in NO_x for Eastern utilities and the lack of low NO_x technologies, more high LOI ash is anticipated to be produced in coming years.

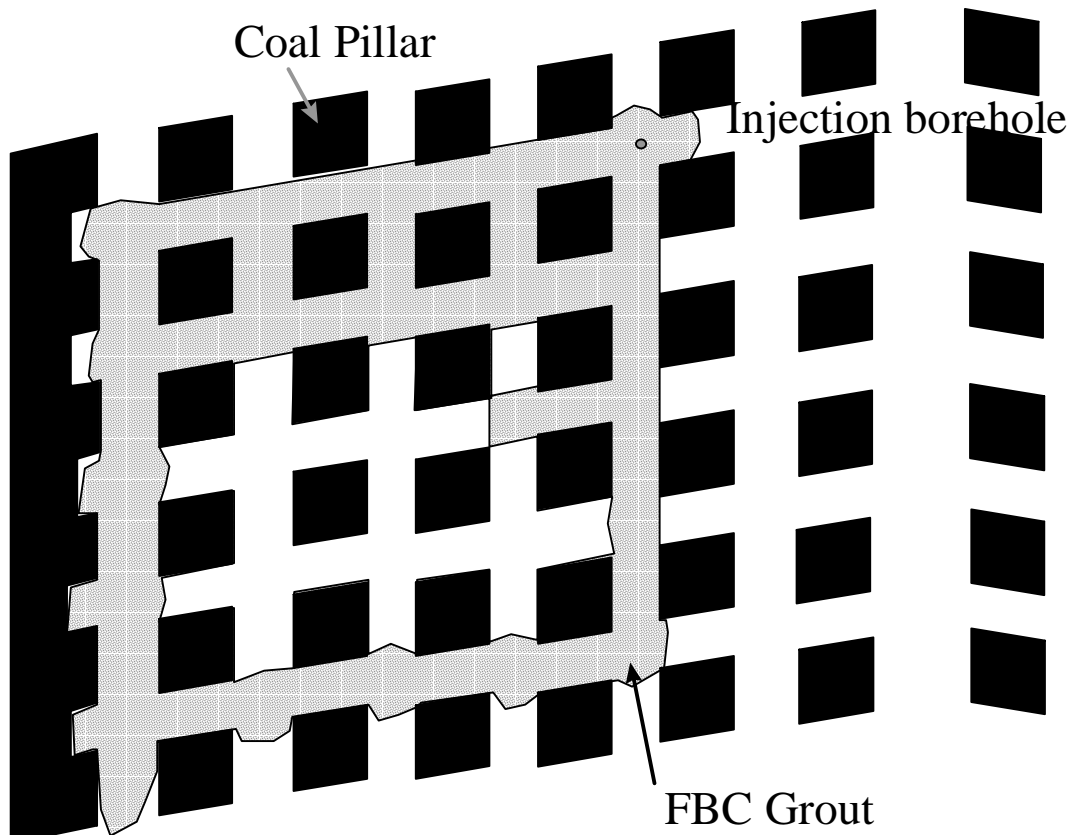


Figure 6 Plan view of Fairfax Mine showing area covered by Phase II grouting.

The high LOI ash is near neutral in pH and does not exhibit any pozzolanic activity (cementitious hardening). A pozzolan source is needed in order to make a grout. Also a pozzolan that is economical and that will not hinder the flow properties of the grout is also needed. Initial experiments were conducted with Portland cement but the economics simply do not work. Portland cement sells for about \$75 per ton and has seen four price increases in as many years. A waste product that would meet the flow and strength requirements was sought. Again, a backhaul arrangement was considered since the transportation costs would be offset from the fuel transport. Such an arrangement was found with Capitol Cement Corporation in Martinsburg, West Virginia. Capitol buys coal from Anker and was landfilling its cement kiln dust at the onsite limestone quarry. Grout formulation test (identical to the FBC ash methodology presented above) were performed and an arrangement was made to procure the CKD and stockpile it for the Phase III operations. Results of the flow tests will be presented during the presentation.

Acknowledgments

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